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DENSITY OF HOT-ROLLED AND HEAT-TREATED CARBON STEELS

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ABSTRACT

In this report are given density values for commercially pure and electrolytic iron and a series of carbon steels, varying from 0.09 to 1.29 per cent carbon. Density values are given for these steels when hot-rolled, when annealed, when quenched, and when quenched and tempered. The steels were quenched in water. The sections of the specimens and the quenching temperatures were varied with the carbon content; the smallest section and highest quenching temperature being used for the steel of lowest carbon content. After quenching, these steels were tempered at successively higher temperatures up to 600° C., and density determinations made after each treatment.

CONTENTS

I. INTRODUCTION

Density is one of the fundamental physical properties of a material. With density data at hand tables may easily be compiled giving weight per foot for steel bars of different compositions and cross section. Very little data are at hand on this subject. Handbooks give approximate values for density of iron and steel as 7.8 to 7.9. These values are to be used for irons and steels, taking no account of the composition or previous history of the metal; that is, whether it is in the condition cast, mechanically worked, or heat treated. The material may be mechanically worked hot or cold. Heat treatment includes annealing, normalizing, and quenching and tempering. Very little has been published on the density of irons and steels subjected to these different treatments. In most investigations density determinations were made to supplement other tests, and not with the idea of providing general information for the various types of steel and the conditions under which they were tested.

Even large steel companies have several times inquired for information regarding the specific gravity, the density or weight per cubic inch or cubic foot of the various classes of steels. As a result of these requests, and because no coordinated set of values for the

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density of different metals and alloys was available, the bureau decided to gather data on carbon and typical alloy steels. This report deals with the first group comprising the carbon steels.

II. PREVIOUS STUDIES OF DENSITY

Andrew and Honeyman (7)[1] made extensive measurements of specific volume on a series of carbon steels and on three nickel-chronium steels.

The carbon steels were heated to 1,000° C., maintained at that temperature for one hour, and slowly cooled in the furnace. With the exception of one composition all values lie on or very close to a straight line for which the equation is

$$\text{Specific volume} = 0.12712 - 0.00052\ C$$

where C is the percentage of carbon. The values obtained were converted to density values and are plotted in Figure 1.

The carbon steels were also quenched in iced brine after being maintained for one-half hour at a temperature of 900° C. They were then tempered at 150° to 160° C., 250° C., 350° to 360° C., and 640° to 660° C. The density values obtained after each of these treatments are plotted in Figure 2. The curve for the quenched steels shows an almost linear increase in the specific volume (decrease in density) up to 0.9 per cent carbon, after which the rate of increase falls. These authors state this is undoubtedly due to the retention of more austenite in the high-carbon than in the low-carbon steels.

Tempering at 150° C. decreased the specific volume. Tempering at 250° C. produced practically no further change in the specific volume in most steels. Andrew and Honeyman stated that this was due to tempering of both austenite and martensite at the same time, the increase in specific volume due to the tempering of austenite being balanced by the decrease in specific volume due to the tempering of the martensite. Tempering at higher temperatures caused a further decrease of specific volume which ultimately approached the value for the annealed steel.

Levin and Dornhecker (2) determined the density of a series of carbon steels in the hot-rolled and also in the annealed condition. For the hot-rolled material an almost straight-line decrease in density was noted with increase in carbon. The values obtained are plotted in Figure 4.

For the annealed material practically a straight-line decrease in density was obtained with increase in carbon content up to about 1 per cent. Above 1 per cent carbon the density of these steels drops

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[1] Numbers in parentheses here and throughout the text refer to the bibliography appended to this report.

off rapidly. The investigators ascribe this sudden drop in density to the formation of temper carbon and present micrographs in support of their contention. The density values obtained on annealed steels are plotted in Figure 1.
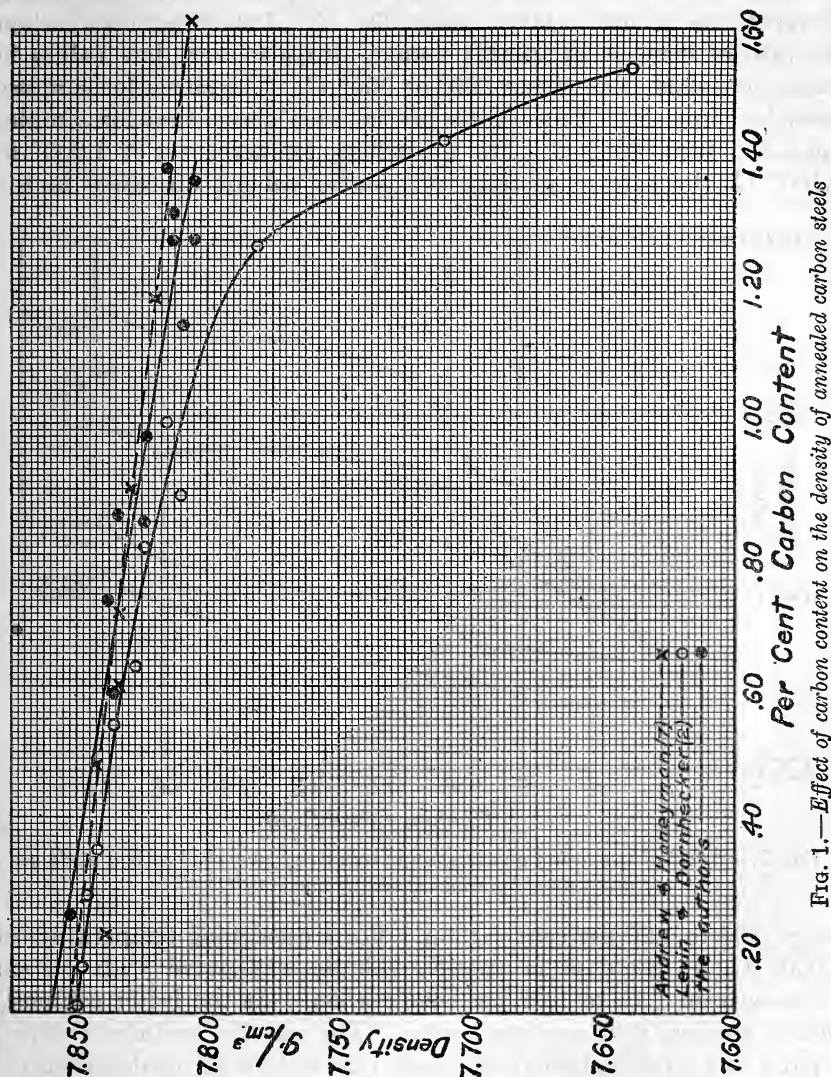

Fig. 1.—*Effect of carbon content on the density of annealed carbon steels*

Andrew, Fisher, and Robertson (11) enlarged on the work done by Andrew and Honeyman. They quenched a series of carbon steels maintaining the size of the specimen constant and varying the quenching temperature. They found an increase in specific volume upon quenching, the increase varying with different quenching temperatures. For steels increasing in carbon up to about 0.75 per cent, when quenched from 800° C., the specific volume increase is

practically linear. Beyond this carbon content the rate of increase
falls off and is practically zero in the steels containing from 1.0 to
1.6 per cent carbon. The increase of specific volume is practically
linear with increase in carbon up to 0.9 per cent for quenching
temperatures of 900°, 1,000°, and 1,100° C. At 0.90 per cent carbon
the rate of increase in specific volume drops to very low values in
steels quenched from either 800° or 900° C. The curve for samples
quenched from 900° C. parallels but is much above that for samples
quenched from 800° C. For quenching temperatures of 1,000° to
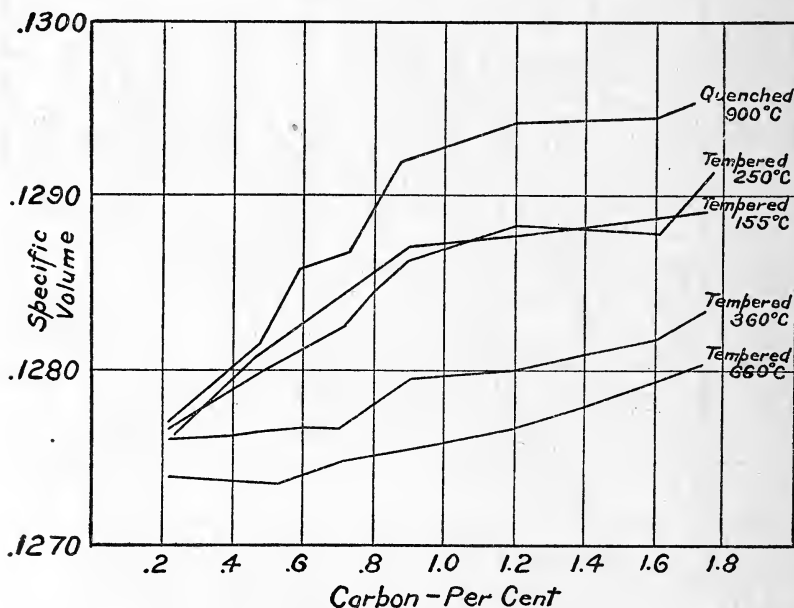1,100° C. the rate of increase of specific volume decreases in the

FIG. 2.—*Effect of tempering on the specific volume of quenched carbon steels as
determined by Andrew and Honeyman (7)*

range 0.90 to 1.20 per cent carbon. For a quenching temperature of
1,000° C. no increase in specific volume was noted with carbon
increase from 1.20 to 1.60 per cent carbon. At the latter composi-
tion a sudden decrease was noted. The specific volume dropped
rapidly in a straight line in the range 1.20 to 1.75 per cent carbon for
steels quenched from 1,100° C., the final value being only slightly
above that for the annealed steel. The values obtained are plotted
in Figure 3.

Hanemann and Schulz (3) made density determinations on four
carbon steels when annealed, when quenched, or when quenched
and tempered. They drew the following conclusions:

The density of quenched carbon steels increases with tempering.
The increase of density is greater for those steels of higher carbon

content since the volume increase on quenching is greater for these
steels.   The increase in density is not uniform as the metallographic
constituents produced on quenching and tempering at given tempera-
tures vary with different carbon contents.   The density increases
with tempering up to 150° C.   At about 150° to 170° C. there is a
decrease in density, this decrease occurring at about 170° C. for
eutectoid steel and for hypo and hypereutectoid steels at a little
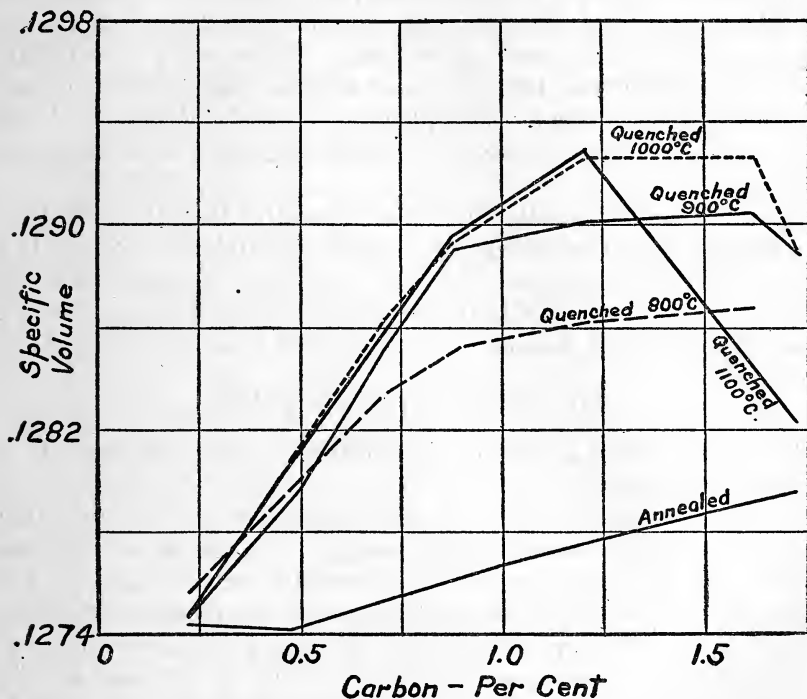lower temperature.   This decrease ends, with hypoeutectoid steel,

Fig. 3.—*Effect of quenching temperature on the specific volume of quenched
carbon steels as determined by Andrew, Fisher, and Robertson (11)*

at a little below 200° C.; with eutectoid and hypereutectoid steel, at
a little above 200° C.   It is of greater magnitude for the higher
carbon contents.   Upon tempering above 200° C. the density again
begins to increase and reaches a maximum at about 430° C.   For
further increase in tempering temperature very little change in
density was noted.   The differences in density resulting from dif-
ferences in carbon content were most apparent in the quenched
condition, diminished on tempering, the smallest differences being
noted after tempering at 430° C.

With regard to other elements ordinarily found in commercial
steels, Benedicks (1) states that the specific volume of iron is raised

by the presence of 1 per cent of each of the following elements to the extent shown:

Element: Increase in the specific volume
    Manganese_____ 0. 00006
    Phosphorus_____:_____ . 00089
    Silicon_____ . 00117
    Hardening carbon_____ . 00180
    Aluminum_____ . 00250

It is known that the density of ordinary carbon steels is decreased by cold working and that the change produced is dependent both on the amount and manner of deformation. Goerens (14) and Ishigaki (12) have studied the density of cold-worked steels, but little quantitative data are at hand. This phase of the study of density of steels will not be considered here, but will be taken up in a subsequent report.

Other studies of density have been made by Ishigaki (12), Doerr (4), Heindlehofer and Wright (9), Honda (6), and Scott (13). Their work was along somewhat different lines, and in some cases alloy steels were studied. While their work is of importance in throwing light on the general density problem little of it needs to be reviewed here.

III. EXPERIMENTAL WORK

Density determinations upon the different steels were made in the following manner:

The weight of the sample in air was determined and then the sample was immersed in water and the weight of water displaced determined. The weight in air was corrected for air buoyancy, and the mass in vacuo was calculated. The mass in vacuo of the water displaced by the sample divided by the density of the water at the temperature of observation equals the volume of the sample. The density of the sample was then found according to the equation $D = \frac{M}{V}$ in which D = density, M = mass of sample (vacuo), and V = volume of sample. All density determinations were made at 20° C.

All samples tested were taken from material used in previous investigations and steel in stock for which analysis was available and for which the previous history was known.

Before studying the density of alloy steels it was decided to establish a base line, using pure irons and carbon steels. Accordingly samples of commercially pure and electrolytic irons and carbon steels ranging in carbon content from 0.09 to 1.29 per cent were obtained. This report deals only with these iron and carbon steel specimens. Some

of the pure irons were hot-rolled and some were in the annealed condition.   The compositions are listed in Table 1.

Density determinations were first made on the steels in the hot-rolled condition, after which the various heat treatments were carried out, the density being determined after each treatment.

TABLE 1.—*Chemical composition of the irons and steels tested*

Sample No.	C	Mn	P	S	Si	Cr	Ni	Cu
	Per cent	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*
171	0.001			0.011	0.004			
F77	.027	0.09		.023	.003	0.055		
VI	.017							
914	.01	Nil.	0.020	.007	.01			
1A	.09	.035	.006	.043	.10			
5A	.28	.56	.008	.019	.07	.087	0.008	0.036
6A	.35	.78	.035	.032	.15			
7A	.44	.81	.025	.022	.14			
8A	.47	.67	.015	.039	.19			
9A	.60	.66	.040	.022	.11			
10A	.68	.70	.031	.025	.17			
11A	.87	.38	.010		.14			
12A	.98	.37	.018	.015	.12			
C8	1.05	.36	.014	.047	.007	.05	.232	.014
C22	1.29	.23	.017	.017	.23	.05		

In the study of the heat-treated steels, a series of 11 steels varying in carbon content from 0.09 to 1.29 per cent was quenched in water and subsequently tempered at successively increasing temperatures up to 600° C.   In quenching these steels the size and shape of specimen, quenching temperature, and coolant used were selected to give maximum amounts of martensite.   The specimens were 6 inches in length, ¾ inch in width, and ¾ to ⅛ inch in thickness, with the thickness varying from ¾ inch for the highest carbon steel to the thinnest section for the lowest carbon steel.   All of the specimens were quenched in water (at 20° C.) from the temperatures indicated in the tables.   The choice of conditions was based on data presented in a paper by French and Klopsch (10).   It will be seen that the quenching temperature, the size of the specimen and, in particular, the section were varied as the carbon content increased; the higher quenching temperatures and smaller sections were used for the steels of lowest carbon contents.   Density determinations were made after quenching.   The specimens were then subjected to successive temperings for one hour at 150°, 225°, 300°, 375°, 460°, 525°, and 600° C.   Tempering at 150°, 225°, and 300° C. was carried out in an oil bath; at 375°, 460°, 525°, and 600° C., in an electric muffle furnace. After each treatment and before density determinations were made, each specimen was carefully sand-blasted to remove all traces of scale which might introduce errors into the determinations.

IV. EXPERIMENTAL RESULTS

The following values are given by earlier investigators for the density of pure iron:

Density
g/cm³

Andrew and Honeyman (7) (annealed)_____ 7. 864
Kaye and Laby (5)_____ 7. 86
Benedicks (1)_____ 7. 85
Levin and Dornhecker (2) (annealed)_____ 7. 871

Average_____ 7. 862

Results obtained by the authors on pure irons are as follows:

Sample No.	Treatment	Density
		g/cm³
171	Vacuum fused electrolytic iron, hot-rolled_	7. 8685
F77	Annealed at 775° C_____	7. 8547
VI	Annealed at 900° C_____	7. 865
914	Vacuum fused electrolytic iron_____	7. 867
	Average_____	7. 864

NOTE.—The analyses are listed in Table 1.

These samples of "pure" iron contain small percentages of carbon and other impurities, but are representative of the purest commercial and electrolytic irons which are available at the present time. It may be seen that marked differences in treatment and previous history do not cause any appreciable variation in the density of these pure irons. The values obtained check quite closely those obtained by other investigators. An average of the density of the four samples gives 7.864 g/cm³, which agrees well with the average of previous determinations.

The steels tested are the usual type of commercial carbon steels, the exact analyses being shown in Table 1. The manganese, phosphorus, sulphur, and silicon present have an effect on the density of the steel which must be considered when pure iron is considered as the base line for comparing the effect of carbon. Benedick's (1) data, by which correction can be made for the presence of these impurities, have already been tabulated in this report. No effort has been made to make these corrections as all the steels fall into a general commercial class.

The density values for the hot-rolled carbon steels are summarized in Table 2 and Figure 4; for the annealed steels in Table 3 and Figure 1; for the quenched and quenched and tempered steels in Table 4 and Figures 5 and 6.

TABLE 2.—*Density of hot-rolled carbon steels*

Carbon content	Density	Carbon content	Density
Per cent	*g/cm³*	*Per cent*	*g/cm³*
0.09	7.848	0.60	7.838
.16	7.857	.65	7.831
.25	7.853	.73	7.839
.28	7.850	.76	7.829
.35	7.839	.87	7.832
.44	7.839	.98	7.822
.45	7.841	.98	7.828
.47	7.833	1.12	7.819
.49	7.834	1.13	7.822
.59	7.836	1.28	7.812

TABLE 3.—*Density of annealed carbon steels*

Carbon content	Density	Carbon content	Density
Per cent	*g/cm³*	*Per cent*	*g/cm³*
0.25	7.852	1.15	7.809
.59	7.836	1.28	7.805
.73	7.838	1.28	7.813
.85	7.824	1.32	7.813
.86	7.834	1.37	7.805
.98	7.823	1.39	7.816

TABLE 4.—*Density of quenched and tempered carbon steels*

Steel No.	Carbon content	Quenching temperature	Density									
			Hot-rolled	Water quenched	Tempering temperature							
					150° C.	225° C.	300° C.	375° C.	460° C.	525° C.	600° C.
	Per cent	° *C.*	*g/cm³*	*g/cm³*	*g/cm³*	*g/cm³*	*g/cm³*	*g/cm³*	*g/cm³*	*g/cm³*	*g/cm³*
1A	0.09	910	7.848	7.823	7.829	7.809	7.830	7.838	7.845	7.839	7.841
5A	.28	865	7.850	7.829	7.837	7.833	7.839	7.842	7.846	7.846	7.844
6A	.35	865	7.839	7.802	7.811	7.816	7.829	7.830	7.828	7.829	7.829
7A	.44	820	7.839	7.802	7.805	7.809	7.824	7.833	7.834	7.834	7.831
8A	.47	820	7.833	7.795	7.796	7.801	7.818	7.825	7.828	7.828	7.831
9A	.60	810	7.838	7.785	7.794	7.797	7.818	7.827	7.829	7.828	7.832
10A	.68	810	7.832	7.776	7.788	7.789	7.809	7.821	7.824	7.826	7.827
11A	.87	795	7.832	7.769	7.784	7.784	7.810	7.824	7.826	7.826	7.830
12A	.98	795	7.828	7.762	7.780	7.776	7.804	7.818	7.821	7.823	7.823
C8	1.05	795	7.825	7.770	7.795	7.792	7.814	7.818	7.821	7.821	7.822
2A	1.12	795	7.819	7.757	7.781	7.770	7.785	7.805	7.809	7.807	7.813
C22	1.29	795	7.812	7.758	7.780	7.767	7.787	7.802	7.805	7.807	7.808

The curve for the hot-rolled samples plotted in Figure 4 shows a gradual drop in density with increasing carbon content. The drop is from about 7.848 for the 0.09 per cent carbon steel to about 7.812 for the 1.29 per cent carbon steel. The values lie on or very close to the straight line which may be represented by the equation:

$$\text{Density} = 7.855 - 0.032 \; C$$

where C is the percentage of carbon. It may be seen that the values obtained agree quite closely with those of Levin and Dornhecker.

The curve for the annealed specimens plotted in Figure 1 also shows a gradual drop in density with increasing carbon content. The drop is from about 7.852 for the 0.09 per cent carbon steel to about 7.805
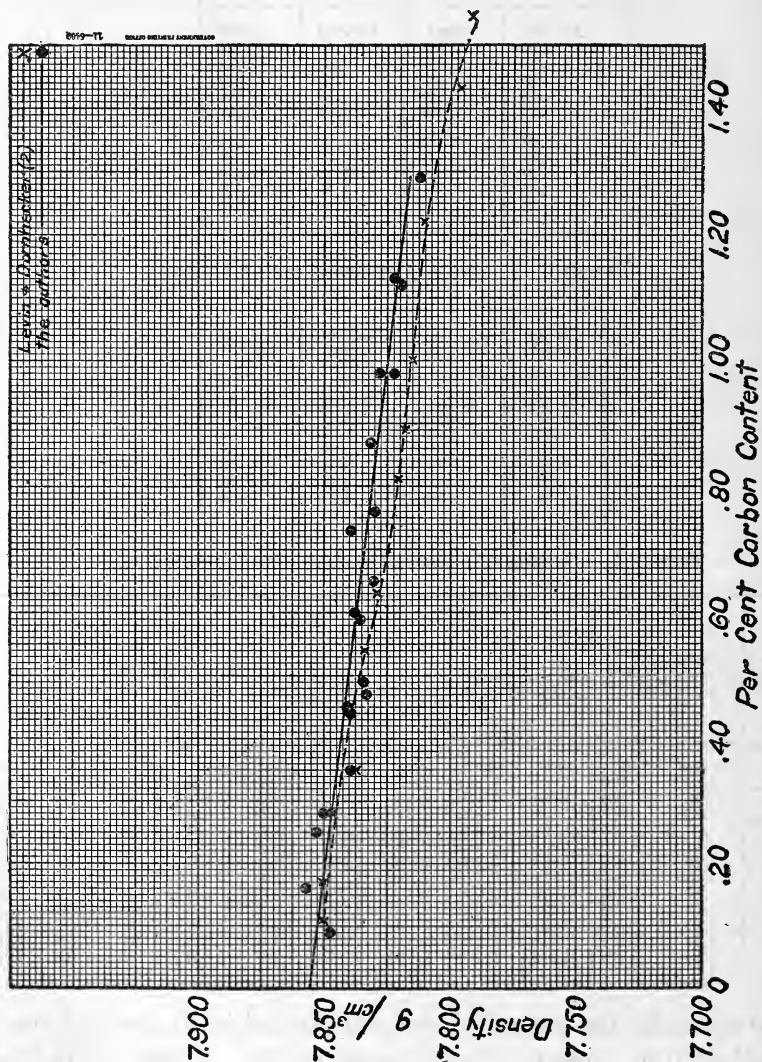

FIG. 4.—*Effect of carbon content on the density of hot-rolled carbon steels*

for the 1.37 per cent carbon steel. The values lie on or very close to the straight line which may be represented by the equation:

$$\text{Density} = 7.860 - 0.040\ C$$

where C is the percentage of carbon. It may be seen from the figure that the curve obtained by the authors agrees quite closely with that of Andrew and Honeyman. The values obtained by Levin and Dorn-

hecker are lower throughout the whole range and drop markedly for the high-carbon contents. This, they claim, is due to the formation of temper carbon.

A decided decrease in density was noted for all steels in the quenched condition. Up to a carbon content of about 1.00 per cent, this de-
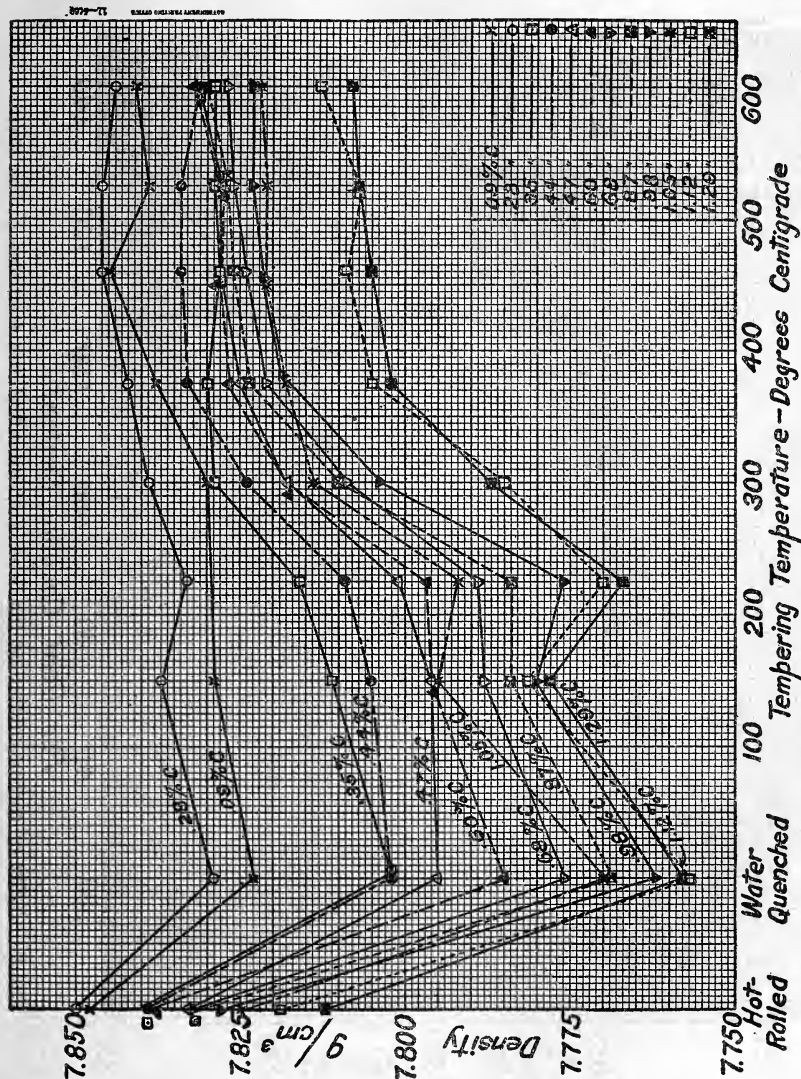

FIG. 5.—Effect of quenching and tempering on the density of hot-rolled carbon steels

crease was greater in magnitude as the carbon content increased. For steels above 1.00 per cent carbon this decrease on quenching fell off slightly. These results are plotted in Figure 7. This decrease of density upon quenching may be attributed to the formation of martensite, since these steels were quenched for the formation of

maximum martensite, and martensite is known to have a lower density than pearlite or austenite.

Upon tempering at 150° C. all of the steels showed an increase in density, the larger increase being noted for those steels of higher-carbon content . (Table 4, fig. 5.) This may be attributed to a partial
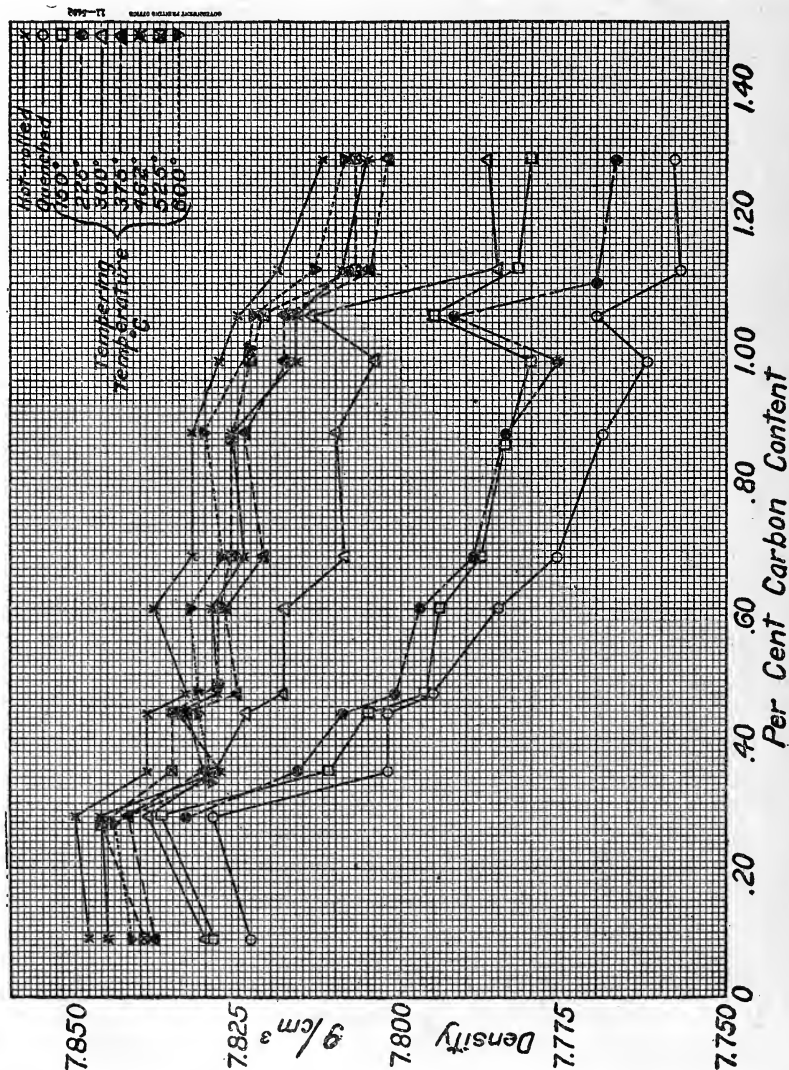

FIG. 6.—*Effect of carbon content on the density of quenched and tempered carbon steels*

tempering of the martensite. Tempering at 225° C. gave some interesting results. The low-carbon steels, with one exception, showed a further increase in density. The steel of eutectoid composition showed no change in density and the hypereutectoid steels showed a decrease in density. This may be attributed to the effect of tem-

pering of retained austenite.   Austenite is more dense than martens-
ite and when tempered would cause a decrease in density of the steel.
Apparently both austenite and martensite are tempered at 225° C.,
the effect of the tempering of the austenite predominating and causing
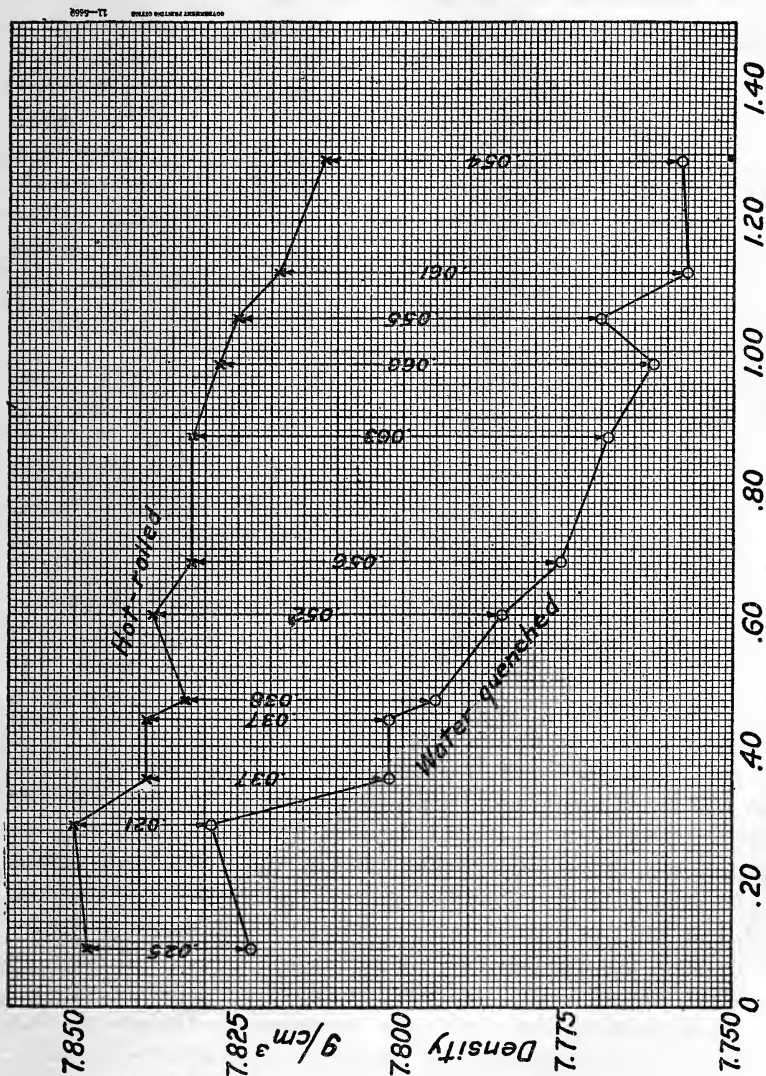the increase in density due to the tempering of the martensite to be

FIG. 7.—*Variations in the density produced by thermal treatments in relation to those produced by changes in carbon content in carbon steels*

overshadowed and neutralized by the decrease due to the tempering
of the austenite.

When the tempering temperature was raised from 225° to 300° C.
increase in density was noted for all samples.   Upon further tem-
pering the rate of increase of density falls off, becoming practically
zero at 600° C.   These data are plotted in Figure 5.

The values for the quenched steels were plotted in a different manner in Figure 6. This figure shows clearly how the density rises with increasing temperature, approaching the density as before quenching, with the largest increase usually being found on tempering at 300° C. It also shows how the density for any one treatment gradually decreases with increase in carbon.

This figure shows up several peculiarities in the results which careful checking by the use of duplicate specimens of the same steel failed to change. For example, all values for the 0.28 per cent carbon steel are high; that is, the values are seemingly in the right order but displaced upward. Also, the values for the 1.05 per cent carbon steel when quenched and tempered at 150°, 225°, and 300° C. likewise seem high. The silicon content for the 1.05 per cent carbon steel is lower than that of the other steels and may account for the higher density values obtained. However, it seems that if this is the cause, higher density values should also be obtained when tempered at the higher temperatures of 375°, 460°, 525°, and 600° C.

Spectrochemical analyses were made on the 0.28 and 1.05 per cent carbon steels. Analysis by means of their arc spectra showed the presence of chromium, nickel, and copper in these steels but no heavier metals. Chemical analyses were made for these elements and the results obtained are indicated in Table 1. The amounts of these impurities present should have but a small effect on the density of these steels.

Enlund (8) made resistivity measurements on quenched carbon steels of varying composition as the tempering temperature was increased. He found two inflections in the curves, one between 110° to 120° C. and another between 250° to 260° C., depending upon whether the carbon content of the steel is high or low. The inflections are visible in all of Enlund's curves, thus indicating that the same reactions occur in all the steels. He concludes that the first break in the curves is due to the transformation of martensite into troostite and the second to the splitting up of austenite into α iron and cementite. He quenched samples of four steels of 0.58, 0.83, 1.22, and 1.57 per cent carbon and tempered these specimens for half an hour at successively increasing temperatures differing by 10° to 20° C. through the range up to 390° C. Specific volume determinations were made after each treatment. The curves obtained show a volume contraction (increase in density) beginning at a temperature somewhat below 100° C., and this proceeds continuously until the tempering temperature is raised to about 210° C., when a pronounced expansion or decrease in density sets in, reaching its maximum at 225° to 300° C. These data check the conclusions drawn from the resistance measurements. Conclusions drawn by Enlund agree with the results obtained in the present investigation.

V. SUMMARY AND CONCLUSIONS

The average density of pure iron was found to be about 7.864 grams per cubic centimeter.

Carbon steels, as hot-rolled, show a gradual decrease in density with increasing carbon content up to about 1.3 per cent and the values lie on or close to the straight line which may be represented by the equation:

$$\text{Density} = 7.855 - 0.032\ C$$

where C is the percentage carbon.

Annealed carbon steels show a gradual decrease in density with increasing carbon content up to about 1.4 per cent and the values lie on or close to the straight line which may be represented by the equation:

$$\text{Density} = 7.860 - 0.04\ C$$

where C is the percentage carbon.

Carbon steels (up to 1.30 per cent carbon) decrease in density when quenched due to the formation of martensite. The magnitude of this decrease rises with increasing carbon content, reaching a maximum at about 1 per cent carbon, and then falls off slightly. Upon tempering the quenched steels gradually increase in density. A decrease in density is noted in the hyper-eutectoid steels when tempered at 225° C. and this may be ascribed to the tempering of retained austenite. Upon further tempering above 225° C. the density of all samples increased, ultimately approaching the density of the annealed steel upon tempering at 600° C. The greatest increase in density occurs upon tempering at 300° C., the rate of increase then gradually falls off as the tempering temperature is raised to 600° C.

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